6. U.S. Pacific Islands Region Acidification Research

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Abstract

The Pacific Islands region includes the exclusive economic zones surrounding a diverse collection of islands and atolls — including the State of Hawaiʻi, the Territories of American Samoa and Guam, the Commonwealth of the Northern Marianas Islands, and the U.S. Pacific Remote Island Areas — that are widely scattered across the western and central Pacific Ocean and separated by many thousands of kilometers of vast pelagic waters. Much of the region is uninhabited and federally protected, and these ecosystems generally experience relatively low levels of local anthropogenic stress. However, the Pacific Islands are significantly impacted by global forcing, including basin-wide climate variability such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation, and global climate change. This region is home to vibrant coral reef ecosystems, numerous threatened and endangered species, and economically- and culturally-significant fisheries supporting commercial industries and local communities. NOAA's Pacific Islands Region research goals are to:

- Maintain existing and develop new ocean acidification (OA) monitoring sites co-located with biological surveys of coral reef and broader marine ecosystems to improve understanding of OA progression and response to be used in real-time forecasts for risk assessment and decision making;
- Integrate physical, chemical, biological, and ecological data to assess ecosystem-wide direct and indirect impacts of OA, with an emphasis on key Pacific marine species; and
- Couple environmental, ecological, human-use, and non-use valuation models to assess OA impacts to human well-being and develop effective ecosystem-based management strategies and relevant science communication tools.

Figure 6.1. Map of archipelagic and island areas included under the U.S. Pacific Islands region and U.S. Exclusive Economic Zone boundaries.

Acidification in the U.S. Pacific Islands Region

The U.S. Pacific Islands region includes the exclusive economic zones surrounding the State of Hawaiʻi, the Territories of American Samoa and Guam, the Commonwealth of the Northern Marianas Islands, and the U.S. Pacific Remote Island Areas (**Figure 6.1**). The region encompasses biologically-diverse coral reef ecosystems; supports culturally- and economically-valuable commercial, subsistence, and recreational fisheries; and is home to numerous threatened and endangered species. The rich diversity and abundance of marine life and associated ecosystem services are vital for the health, culture, coastal protection, and economic viability of Pacific Island communities.

The Pacific Islands region covers an immense geographical area (5.82 million km^2) that spans dramatic gradients in oceanographic conditions, ranging from the relatively stable, oligotrophic North and South Pacific Subtropical Gyres to the dynamic upwelling zones of the central equatorial Pacific. Many of the islands and atolls in the Pacific Islands region are uninhabited, remote, and federally protected as National Wildlife Refuges and Marine National Monuments. As a result, these ecosystems experience relatively low levels of local anthropogenic stress, but are significantly impacted by global forcing, including climate variability and climate change (Polovina et al., 2016). Natural climate modes that exert influence in the region include the El Niño Southern Oscillation and the Pacific Decadal Oscillation, which drive large interannual and decadal shifts in ocean temperatures, winds, vertical mixing, equatorial upwelling strength, and seawater carbonate chemistry that influence the structure and function of coral reef and pelagic ecosystems (Brainard et al., 2018; Sutton et al., 2014b). Within the past several decades, the progressive acidification of open ocean surface waters has occurred in concert with rising atmospheric and surface seawater carbon dioxide (CO_2) concentrations. The 30-year Hawai'i Ocean Time-series has documented significant decreasing trends in surface seawater pH of 0.0016-0.0019 yr^{-1} in the North Pacific Subtropical Gyre (Bates et al., 2014a; Dore et al., 2009; **Figure 6.2**), and pH has declined 0.0018-0.0026 yr^{-1} in the central equatorial Pacific between 1998 and 2011 (Sutton et al., 2014b).

Coral reefs form the structural foundation for most of the island ecosystems in the region and provide substantial ecosystem goods and services to local communities through fisheries, tourism, and coastal protection (Bishop et al., 2011; Brander & van Beukering, 2013; Moberg & Folke, 1999; Storlazzi

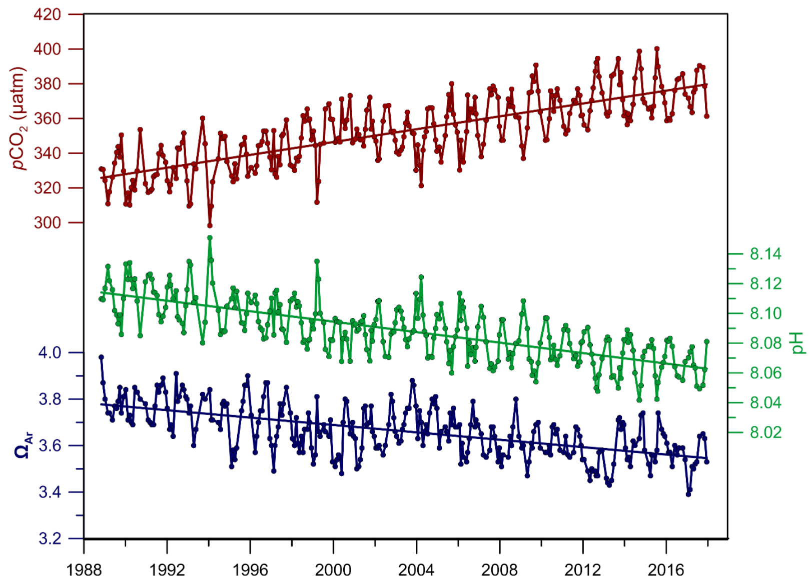

Figure 6.2. Time series of mean surface carbonate system parameters measured at Station ALOHA, 100 km north of O'ahu, Hawai'i (22.75 °N, 158 °W), 1988–2017. Partial pressure of carbon dioxide (pCO_2), pH (total scale), and aragonite saturation state (ΩAr) were calculated from dissolved inorganic carbon (DIC) and total alkalinity (TA). Linear regression fits are overlaid. Adapted from Dore et al. (2009)

et al., 2019). These ecosystems are among those expected to be most sensitive to OA (Hoegh-Guldberg et al., 2007; Kroeker et al., 2010). Over the past two decades, NOAA's comprehensive coral reef OA monitoring program has assessed spatial patterns and initiated monitoring of temporal trends in carbon system-related parameters and the biological and ecological components of coral reef ecosystems most likely affected by OA. NOAA data collected on U.S. Pacific coral reefs have: 1) established carbonate chemistry baselines around 38 islands (**Figure 6.3**); 2) documented spatial patterns and drivers of reef calcium carbonate accretion around 31 islands (**Figure 6.4**); 3) initiated assessments of reef bioerosion and dissolution at 13 islands; and 4) described cryptobiotia and microbial community diversity and abundance at 13 islands. The exposure to and impacts of OA within the vast pelagic and deep-sea ecosystems of the region remain much more poorly characterized.

Environmental Change in the U.S. Pacific Islands Region

Assessing spatial patterns and temporal trends in OA in coral reef and pelagic ecosystems is a high priority for NOAA's environmental monitoring in the Pacific Islands region. Since 2000, NOAA has conducted biennial or triennial coral reef monitoring at 38 Pacific Islands as part of the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) and, since 2013, as part of the National Coral Reef Monitoring Program (NCRMP). In 2005, NOAA initiated monitoring of carbonate chemistry and key OA-related ecological indicators. These sampling efforts have established baseline means and spatial variability in nearshore environments across the Pacific Islands region (**Figure 6.3**). In the open ocean, the international observing collaboration established under the Global OA Observing Network (GOA-ON) has provided OA data integrated from repeat ship-based hydrography, volunteer observing ships, time-series stations, and moorings for the Pacific pelagic areas that support important commercial fisheries and highly-migratory protected species (see Open Ocean Region, Chapter 2). There is currently no comparable OA observing network for mesophotic and deep-sea coral reef environments.

Paired with spatially-broad, but temporally-sparse *in situ* sampling, moored autonomous OA sampling arrays provide near-continuous monitoring of chemical, physical, and meteorological conditions at sentinel sites. These high-resolution time series offer baseline data on diel, seasonal, and interannual variability in carbonate chemistry and can be used to detect long-term acidification trends. Sustained observations are especially important in nearshore coral reef environments, where secular trends in pH can be difficult to discern due to highly variable biogeochemical conditions (Sutton et al., 2019). In the Pacific Islands region, NOAA and the University of Hawaiʻi have maintained Moored Autonomous *p*CO_2 (MA*p*CO_2) buoys at several open ocean stations (WHOI Hawaiʻi Ocean Time-series, equatorial Tropical Moored Buoy Array) starting in 2004 and at four nearshore sites around Oʻahu, Hawaiʻi (Ala Wai, Kilo Nalu, Kaneʻohe Bay, CRIMP/CRIMP 2) starting in 2005. An additional buoy was deployed in Fagatele Bay, American Samoa in 2019.

Characterizing regional-scale OA patterns and trends across the broad oceanographic gradients of the Pacific Islands presents an enormous challenge. However, spatially-explicit, seasonal and annual carbonate chemistry datasets and OA forecasts (e.g., Gledhill et al., 2008) that project variability in OA exposure and identify possible hotspots or refugia can be useful management tools. Upscaling *in situ* observations, developing coupled hydrodynamic and biogeochemical models, and integrating remote sensing and model data to create hindcast and predictive OA spatial products are therefore high priority research needs for the Pacific Islands to support regional decision making and management strategy evaluation.

Research Objective 6.1: Continue monitoring and assessment of OA in coral reef ecosystems

Nearshore OA monitoring is essential for tracking temporal and spatial variability in carbonate chemistry and the progression of OA in highly sensitive coral reefs. When co-located with biological assessments and ecological surveys, long-term monitoring can offer an integrated ecosystem perspective of OA impacts on reef ecosystems and provide important baseline data for science-based management strategy.

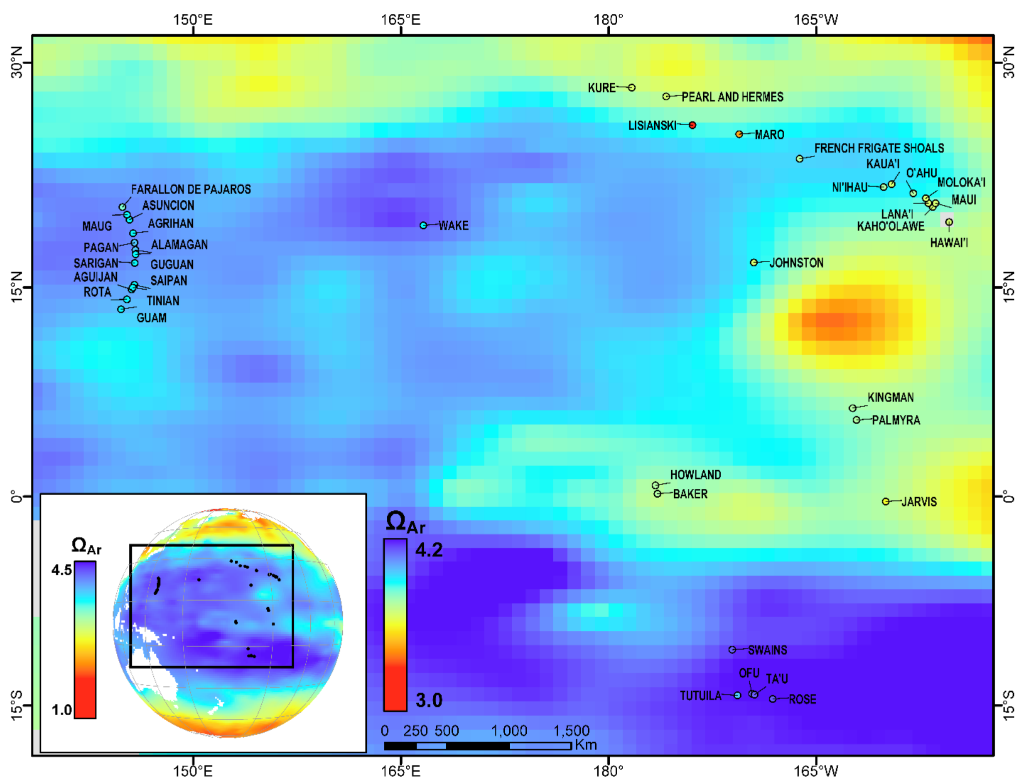

Figure 6.3. Climatological aragonite saturation state (ΩAr) for the Pacific Islands region from the GLobal Ocean Data Analysis Project (GLODAP) v2 (Lauvset et al., 2016). Islands that NOAA surveys as part of the Pacific Reef Assessment and Monitoring Program are shown as points, with shading corresponding to the average 2010-2017 in situ ΩAr (calculated from DIC and TA).

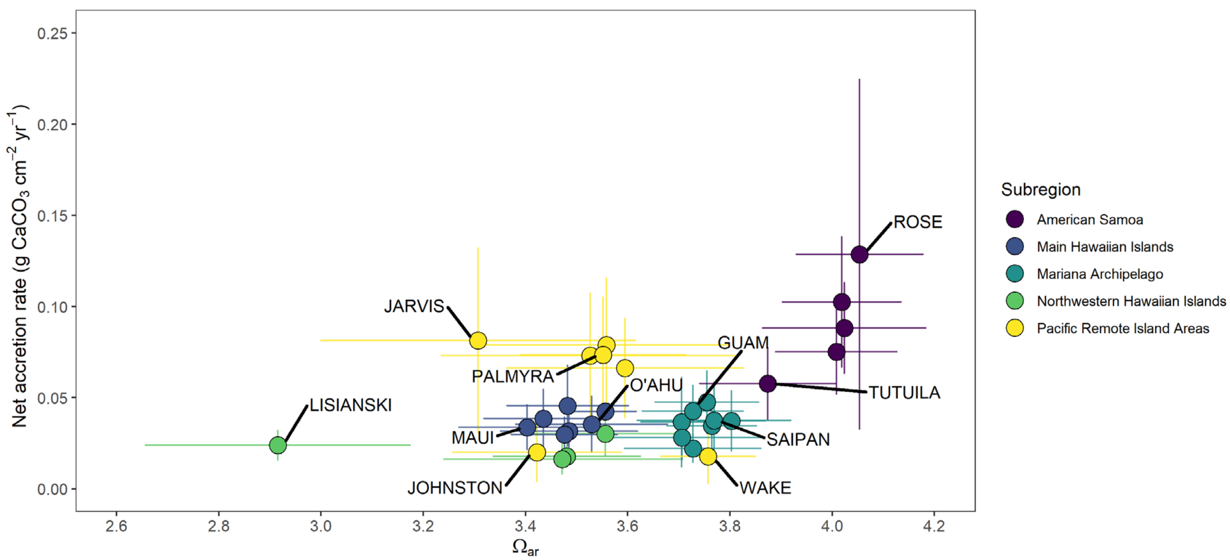

Figure 6.4. Mean (± one standard deviation) in situ ΩAr plotted against mean (± one standard deviation) net calcium carbonate accretion rates (measured from Calcification Accretion Units, CAUs) for 31 Pacific Islands from 2010 to 2017. Islands are colored by subregion, and islands of interest are labelled. See Vargas-Ángel et al. (2015) for additional information on CAUs.

***Action 6.1.1*:** Maintain carbonate chemistry water sampling in shallow coral reef environments and expand nearshore OA monitoring in collaboration with local partners to describe spatial patterns and longer-term temporal trends in OA across Pacific insular areas.

***Action 6.1.2*:** Conduct short-term, high-resolution instrument deployments to measure carbonate chemistry and other physical and biogeochemical parameters (e.g., temperature, salinity, water flow, light, and dissolved oxygen) and contextualize lower frequency observations (*Action 6.1.1*).

***Action 6.1.3*:** Maintain and expand moored autonomous buoy deployments at representative coral reef sites and offshore reference stations and increase coordination and collaboration with other international moored observing networks in the region to document high-resolution temporal variability in carbonate chemistry and capture multi-decadal OA trends.

Research Objective 6.2: Expand regional OA observing system to include pelagic and deep-sea environments

Establishing comprehensive OA monitoring programs in insular mesophotic, subphotic, and deep sea environments and expanding GOA-ON monitoring in U.S. Pacific Islands pelagic waters (in coordination with *Open Ocean Region Chapter 2, Research Objective 2.1*) will improve understanding of spatial and temporal carbonate chemistry variability and enable predictions of OA effects on pelagic and deep sea ecosystems.

***Action 6.2.1*:** Maintain and expand shipboard underway pCO_2, dissolved inorganic carbon (DIC), total alkalinity (TA), and/or pH analyzers on NOAA ships to measure the two or more pelagic surface carbonate chemistry parameters needed to constrain full carbonate system chemistry along cruise tracks.

***Action 6.2.2*:** Deploy autonomous data collectors (e.g., Saildrones, gliders, biogeochemical-ARGO floats) equipped to measure at least two carbon parameters (pCO_2, pH, TA, DIC) and temperature, salinity, and other physical and biogeochemical parameters at the ocean surface and along vertical depth profiles to augment or replace shipboard collections.

***Action 6.2.3*:** Collect subsurface oceanographic data and carbonate chemistry samples along vertical depth profiles to establish baseline carbonate chemistry levels and monitor OA in mesophotic, subphotic, and deep-sea ecosystems.

NOAA divers service instrumentation that monitors acidification near a coral reef at Hawai'i Island. Credit: Paul Cox/Hawai'i Marine Education and Research Center

Research Objective 6.3: Create real-time and forecast OA spatial products

Regional OA maps that leverage available physical and biogeochemical datasets and model output can provide predictive and actionable spatial products. These products can be used to assess OA risk, identify vulnerable species and communities, and advise decision making at spatial scales and time frames relevant to management planning and policy decisions (*in coordination with Open Ocean Region Chapter 2, Research Objectives 2.3 and 2.4*).

Action 6.3.1: Construct time-varying insular and pelagic maps of Pacific carbonate chemistry parameters (pCO_2, pH, Ω_{arag}) using remote-sensing data, assimilative models, and *in situ* sample data to provide regional-scale perspective on spatial patterns and temporal variability in OA.

***Action 6.3.2*:** Couple hydrodynamic and biogeochemical models with climate models to improve understanding of carbonate chemistry dynamics and OA prediction in both pelagic and coastal environments and identify hotspots and refugia.

Biological Sensitivity in the U.S. Pacific Islands Region

Corals, crustose coralline algae, calcareous plankton, and other marine calcifiers are among the Pacific taxa most vulnerable to the direct impacts of OA. In general, OA effects on the growth, reproduction, and survival of many warm water coral reef organisms are now relatively well known (Kroeker et al., 2010). As part of Pacific RAMP and NCRMP monitoring, NOAA has collected data on calcium carbonate accretion and dissolution rates (Enochs et al., 2016a; Vargas-Ángel et al., 2015; **Figure 6.4**); coral calcification and bioerosion (DeCarlo et al., 2015); cryptobiota and microbial diversity; and benthic and fish diversity, density, size structure, and biomass within the U.S. Pacific Islands (Smith et al., 2016; Williams et al., 2015). Of the region's coral reefs, the deep-sea and mesophotic ecosystems exposed to shoaling aragonite saturation horizons may be among the first that OA impacts (Guinotte et al., 2006; Hoegh-Guldberg et al., 2017). However, the OA sensitivity of these communities remains poorly constrained.

The mechanism and severity of possible OA effects on protected and managed species are critical knowledge gaps in the Pacific Islands region. The major pelagic and coastal fisheries — including pelagic longline and purse seine fisheries for tunas and billfish and insular bottom fish, coral reef, and shellfish fisheries — may be susceptible to OA-driven reductions in species growth, fitness, and/or reproduction. Indirect OA impacts to these fisheries could include changes in habitat structure (e.g., changes to coral reef framework production), spawning grounds, food sources (e.g., through shifts in calcareous plankton community structure), or trophic interactions (Cooley & Doney, 2009; Nagelkerken & Connell, 2015). The critically endangered Hawaiian monk seal (*Neomonachus schauinslandi*), endangered hawksbill sea turtle (*Eretmochelys imbricata*), threatened green sea turtle (*Chelonia mydas*), and cetacean species may also be vulnerable to changes in essential feeding, breeding, and/or nesting habitats due to OA effects on seagrass beds and carbonate sand production (Hawkes et al., 2009; Price et al., 2011) and/or shifts in food availability and food web dynamics (Nagelkerken & Connell, 2015).

OA will likely alter the structure and function of marine ecosystems over the next several decades. Therefore, evaluations of climate drivers and ecosystem responses are needed to inform the efficacy of possible management actions (e.g., protecting resilient species and populations, setting fisheries annual catch limits, reducing other stressors that exacerbate OA impacts, direct interventions to reduce OA) at scales relevant to local communities. By driving local-scale interactions with a range of climate scenarios and management strategies, regional models can predict ecosystem dynamics and explicitly address tradeoffs across ocean use sectors. Recent Atlantis ecosystem model studies, including the Guam Atlantis model, have begun to incorporate OA drivers and species responses (Weijerman et al., 2015). However, refining these models will require additional data on downscaled OA projections and sensitivities of local taxa to OA (Marshall et al., 2017).

Big Momma, one of the largest coral heads in the world, can be found in the National Marine Sanctuary of American Samoa. Credit: NOAA

Research Objective 6.4: Assess direct OA impacts on key Pacific coral reef and pelagic species

Maintaining and expanding ecological monitoring, conducting laboratory perturbation experiments on understudied taxa, and synthesizing existing data to constrain the OA sensitivity of key species will improve our understanding of OA impacts on coral reef, mesophotic, deep-sea, and pelagic ecosystems (in coordination with *Open Ocean Region Chapter 5, Research Objective 2.5*).

***Action 6.4.1*:** Assess calcium carbonate accretion and dissolution on coral reefs and deep-sea coral habitats across latitudinal and depth gradients, paired with long-term monitoring of benthic and fish communities, to document the impacts of OA and other stressors on coral reef communities, describe resilience potential, and identify priority areas for management or restoration efforts.

Action 6.4.2: Complete literature reviews and synthesis of OA impacts to growth, fecundity, and mortality of key Pacific species to inform the development of sensitivity scalars of those organisms to decreased pH.

***Action 6.4.3*:** Conduct field assays, laboratory experiments, and multi-stressor studies to measure OA sensitivity for focal taxa (e.g., calcareous plankton, larval fish, shallow and deep-sea corals, mollusks, coralline algae, seagrass, and bioeroders), build OA response curves, and assess effects on trophic and food web interactions.

Research Objective 6.5: Evaluate indirect effects of OA on fisheries and protected species

Pelagic and coastal fisheries and protected species (monk seals, sea turtles, and cetaceans) are regional research and management foci. However, robust OA impact evaluations do not currently exist for these species and populations. Determining the impacts of changes in carbonate chemistry on trophic interactions, essential habitats, and behavior will help project their vulnerability to OA and aid in the effective management of these resources (in coordination with *Open Ocean Region Chapter 5, Research Objective 2.6*).

***Action 6.5.1*:** Integrate plankton and trawl surveys, fish diet studies, fisheries data, stock assessments, and laboratory experiments to assess OA-driven changes to the structure and energy flow of insular and pelagic food webs.

Action 6.5.2: Assess effects of OA on abundance and distribution of seagrass beds and determine associated impacts on sea turtle grazing behavior and habitat availability.

***Action 6.5.3*:** Build carbonate sand budgets for beaches that serve as pupping and nesting grounds for monk seals and sea turtles to help assess the expected magnitude of changes in sand production related to reductions in coral, crustose coralline algae, and calcareous macroalgae calcification rates.

Research Objective 6.6: Determine ecosystem-scale OA impacts

An ecosystem-scale integration of physical, chemical, biological, ecological, and socioeconomic data is required to determine the effects of OA and other stressors on coral reef and pelagic ecosystems, fisheries, and protected species and evaluate management strategies.

***Action 6.6.1*:** Improve ecosystem model parameterizations by synthesizing carbonate chemistry observations, species-specific OA sensitivity data, and response curves (*Action 6.4.2*).

***Action 6.6.2*:** Refine trophic interaction ecosystem models to include OA drivers and taxa responses in order to provide decision-support tools for fisheries and coastal resource management.

Human dimensions in the U.S. Pacific Islands Region

Over the next few decades, OA impacts on marine ecosystems in the Pacific Islands will likely negatively affect ecosystem services, marine resources, and the local human communities who depend on them for their livelihoods, subsistence, wellbeing, and social and cultural continuity (Bennett, 2019; Brander & van Beukering, 2013; Leong et al., 2019; Storlazzi et al., 2019). Therefore, critical research priorities in the Pacific Islands region are evaluating and projecting the effects of OA on marine resource-reliant industries, local fisheries, and human communities, and developing ecosystem-based fisheries management strategies that are driven by OA-informed environmental, ecological, and socioeconomic considerations. As natural resource managers increasingly move toward ecosystem-based approaches and social-ecological-systems frameworks, metrics of human well-being and cultural ecosystem services will be necessary to determine the success of management interventions (Leong et al., 2019).

Recent Atlantis ecosystem model studies, including the Guam Atlantis model (Weijerman et al., 2015), have introduced conceptual models to understand the human dimensions of OA scenarios in the context of fisheries and marine tourism. However, the parameterization of economic impact models and social indicators to understand how OA could affect the vulnerability of natural resource-reliant industries and communities requires further advancements. NOAA has developed an initial framework for assessing community vulnerability for the Pacific Islands region (Kleiber et al., 2018). Ongoing work will focus on improving upon and applying this suite of Community Social Vulnerability Indicators to consider OA impacts on fishing community engagement and reliance.

A diver enjoys the vibrant reefs of the U.S. Pacific Islands. Credit: NOAA

A key challenge in addressing future OA will be securing financial and political investments to develop effective adaptive strategies and solutions. Foundational studies, including work NOAA has conducted as part of the socioeconomic monitoring component of NCRMP, have documented baselines for community understanding and awareness of the threat of OA across the Pacific Islands region (Gorstein et al., 2019, 2018a,b; Levine et al., 2016; Madge et al., 2016). Future studies will be critical to document trends in public awareness and perceptions to inform future planning and investment in local adaptation strategies. It is also imperative to prioritize development of effective science communication techniques and applications to describe potential OA impacts to environmental, biological, economic, and social systems. NOAA should pursue efforts to create visualization products and education and outreach resources in collaboration with NCRMP, local jurisdictions, and other partners that target diverse stakeholders to promote understanding and awareness of OA.

Research Objective 6.7: Assess direct and indirect impacts of OA on Pacific communities

Coupling environmental and ecological dynamics (*Research Objective 6.4*) with human-use sectors and non-use values in ecosystem models will support assessment of OA impacts on marine resource-reliant industries and communities, including impacts to human well-being and ecosystem services.

Action 6.7.1: Identify the relationships of key social, cultural, and economic drivers to biophysical, fishery, and ecosystem parameters to predict potential responses from future OA scenarios.

Action 6.7.2: Create regional economic impact and behavioral models for marine resource-reliant industries to inform consideration of benefits and costs of alternative management strategies to mitigate impacts from OA.

Action 6.7.3: Develop management objectives related to human-use sectors, non-use values, ecosystem services, and well-being, and derive indicators to monitor effectiveness.

Research Objective 6.8: Characterize community awareness and resilience to OA

Integrated assessments of trends in biological conditions, social perceptions, and community vulnerabilities are necessary to develop effective management strategies in Pacific Island communities.

Action 6.8.1: Monitor trends in community awareness and perceptions of OA impacts and participation in stewardship activities across diverse stakeholders and make efforts to link with environmental (*Research Objective 6.2*) and biological sensitivity (*Research Objective 6.3*) trends to understand areas of coherence.

Action 6.8.2: Couple analyses of biological sensitivity (*Research Objective 6.4*) with social vulnerability and adaptive capacity frameworks to inform local community mitigation planning and management.

Research Objective 6.9: Develop innovative OA science communication products for diverse stakeholders

Investments in OA adaptation and management strategies will require effective dissemination of the potential changes, threats, and impacts from future OA scenarios on environmental, biological, economic, and social systems.

Action 6.9.1: Pursue efforts to create visualization products and education and outreach resources targeting diverse stakeholders to communicate scientific findings and promote understanding and awareness of OA processes and potential impacts.

References

[INTRO] = Introduction;

[NAT] = National Ocean & Great Lakes;

[OO] = Open Ocean Region;

[AK] = Alaska Region;

[ARC] = Arctic Region;

[WC] = West Coast Region;

[PAC] = U.S. Pacific Islands Region;

[SAG] = Southeast Atlantic & Gulf of Mexico Region;

[FLC] = Florida Keys and Caribbean Region;

[MAB] = Mid-Atlantic Bight Region;

[NE] = New England Region;

[GL] = Great Lakes Region

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